SCIENCE FOR CERAMIC PRODUCTION

UDC 666.3.046.4:536.3.001.24

CONTROL OF THE TEMPERATURE CONDITIONS OF FIRING IN FURNACES WITH RADIATING WALLS

S. A. Karaush[1] and E. G. Bober'[1]

Translated from Steklo i Keramika, No. 11, pp. 20 – 22, November, 1998.

The possibility of achieving optimum conditions of heat treatment of ceramic articles in furnaces with radiating walls is shown. A function providing control of the thermal energy supply to the firing zone of the furnace is found for the considered example of solid brick firing in the furnace, which makes it possible to obtain high-quality articles at minimum intensity of heat transfer and minimum power consumption.

The problems of development of optimum conditions for heat treatment of ceramic products in firing furnaces are important due to the high power consumption and high cost of energy and fuel resources. The analysis of furnaces for wall ceramics firing in which the heat transfer from the furnace walls to the products is mostly implemented by radiation, revealed the existence of considerable reserves for energy saving [1]. The excessive power consumption in firing furnaces is above all related to the absence of methodology for determining the optimum conditions for heat treatment of ceramic articles, which only lately began to be elaborated [2].

The purpose of the present study is to show the possibility for developing optimum firing conditions for ceramic articles and controlling these conditions in furnaces with radiating walls. Due to the great variety of such furnaces, we restrict ourselves to considering the tunnel furnace described in [1] (a similar furnace currently operates in Kurtamysh, the Kurgan Region). The furnace is used to fire solid bricks made of Naumovskoe clay (Tomskii District) whose thermophysical properties were experimentally determined and described in [3]. The furnace output is 2.8 million bricks per year. The length of the preparation zone is 10 m, the length of the firing zone is 10 m, and the length of the cooling zone is 10 m. A charge placed on a firing car has a height of 1.56 m and a size 1.9×0.56 m in plane and consists of 704 bricks. The maximum heat flow density on the radiating wall in the firing zone can attain 16 kW/m^2. The firing duration is 30 h. The clearance between the vertically placed bricks in the charge was taken to be 66 mm, based on the recommendations given in [4].

The calculation of the temperature conditions for the firing furnace was carried out in accordance with the statement of the problem described in [1]. The values of convective heat transfer from the furnace walls and the products to the gases were found from the known similarity equations. It is assumed that free convection is absent in the channels between the articles in the firing zone, and the heat transfer in them is implemented only by radiation. For the analysis of the firing zone, the charge is considered as a flat parallelepiped consisting of a large number of elementary cells. The sizes of the articles (Fig. 1) are $l = 260$ mm, $2\delta = 67$ mm, $2S = 124$ mm. The other initial data in the numerical calculations of the heat problem were taken as follows: charge density — 0.677; distance from the radiating wall surface to the frontal surface of the articles in the charge — 0.05 m; area of the radiating wall surface of a cell — 0.0254 m^2; frontal area of the surface of the articles in the charge — 0.0172 m; radiating capacity of the furnace walls surface — 0.75, and of the articles — 0.57; thermal massiveness of the furnace brickwork — 9200 kJ/K; firing temperature — 1123 K. The thermophysical properties of Naumovskoe clay are described by piecewise linear functions.

Analysis of the results of calculation of the ceramic charge heating showed that the maximum temperature drop for the entire cycle of heating, firing, and cooling of the articles is observed along the axis of the product, i.e., along the main direction of heat transfer. In this context, we considered a simplified setting of the optimization problem as a one-dimensional problem. The solution of the optimization prob-

[1] Science and Research Institute of Building Materials at Tomsk State Architectural and Construction University, Tomsk, Russia.

0361-7610/98/1112-0349$20.00

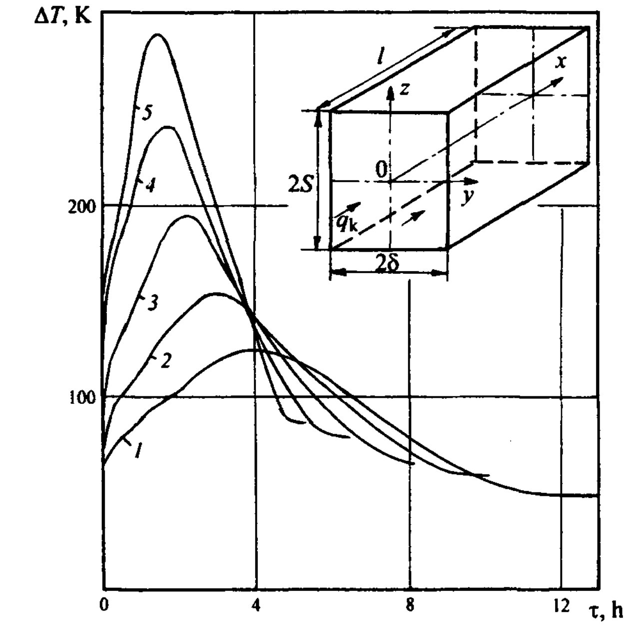

Fig. 1. Temperature drops arising along the article axis ($Y = Z = 0$) between the $X = 0$ and $X = 0.1$ sections depending on the heat flow density on the radiating wall: $X = x/\delta$; $Y = y/S$; $Z = z/l$. *1, 2, 3, 4,* and *5*) heat flow density q_k for 8, 10, 12, 14, and 16 kW, respectively.

lem in addition to the heat problem calls for the analysis of the thermoelasticity problem for fired articles, which was analyzed by S. A. Blokh in sufficient detail for the firing conditions of ceramics [5]. It was demonstrated that in the firing of the majority of ceramic articles (tiles, ceramic bricks, stones, etc.) this problem can be considered as a problem of disconnected thermoelasticity.

In the numerical solution of the heat problem, the values of the local temperatures in the grid nodes for each time step were stored in the computer memory as arrays for the purpose of using them in the optimization problem. It is easy to extract from the statement of the heat problem described in [1] a dependence in the form of an inert component of first order for the control of the heat treatment process in a furnace with radiating walls (when all the coefficients a_i are equal to zero, except for the coefficients a_1 and a_3):

$$P\frac{dT_k}{d\tau} + T_k = k_k V(\tau), \qquad T_k(\tau = 0) = T_{k,0}, \qquad (1)$$

where P is a coefficient which characterizes the component parameters; $T_k(\tau)$ and $T_{k,0}$ are the current and initial temperatures of the radiating surface of the furnace wall, respectively; k_k is a constant; $V(\tau)$ is the effect of controlling the power supplied to the furnace;

The use of a dependence of the type (1) makes it possible to quickly and easily find the optimum parameters for heat treatment of articles. In our opinion, the most plausible optimality criterion for the considered class of problems is the generalized cost criterion [6]. Then the optimization of the heat treatment of ceramic articles can be performed with respect to the generalized cost criterion (the target functional), which for our case is represented in the form

$$I_0 = \frac{P_1}{Mn}\int_0^{\tau_2} V^2(\tau)d\tau + \frac{P_2}{M}\int_0^{l} [T(x,\tau_3) - T_3(x)]^2 dx + \frac{P_3}{M}\int_0^{\tau_3} [\sigma_s(\tau) - \sigma_3(\tau)]^2 d\tau \to \min, \qquad (2)$$

where P_i are price coefficients; M is the mass of a single charge of articles per firing car; n is the number of charges; $T_3(x)$ and $\sigma_3(x)$ are prescribed temperature and thermal stress of the articles;

The first summand in the functional (2) takes into account the consumption of power in the heat treatment of the articles in n charges. The second summand determines the inexactness of heating for the temperature field of the charge of articles at the end of the firing process. The third summand shows a deviation in the thermal stress on the surface of the body σ_s from the prescribed value or the value required by the technology standards (the "perfect" value) σ_p.

The considered thermal and optimization problems are subjected to the following restrictions:

controlling effect

$$V_{\min} \le V(\tau) \le V_{\max}; \qquad (3)$$

a temperature of the article surface

$$T_s(\tau) \le T_{s,\max}; \qquad (4)$$

a temperature of the radiating wall surface

$$T_k(\tau) \le T_{k,\max}; \qquad (5)$$

a thermal stress

$$\sigma_p(\tau) \le \sigma_{\max}(\tau), \qquad (6)$$

where $\sigma_{\max}(\tau)$ is the permissible value of thermal stress in an article.

In order to determine the optimum controlling effect, the variation calculation using the Lagrange method of indefinite multipliers was applied [6]. For this purpose, the variation problem was reduced to a boundary problem and written in variations. The variation was determined from the relationship

$$\delta J = \int_0^{\tau_p} \left[\frac{2P_1V(\tau)}{Mn} - \Psi_0(\tau)(a_3 - a_4T_k)\right]\delta V d\tau,$$

where Ψ_0 is a Lagrange multiplier of first order determined from the obtained conjugated equation system.

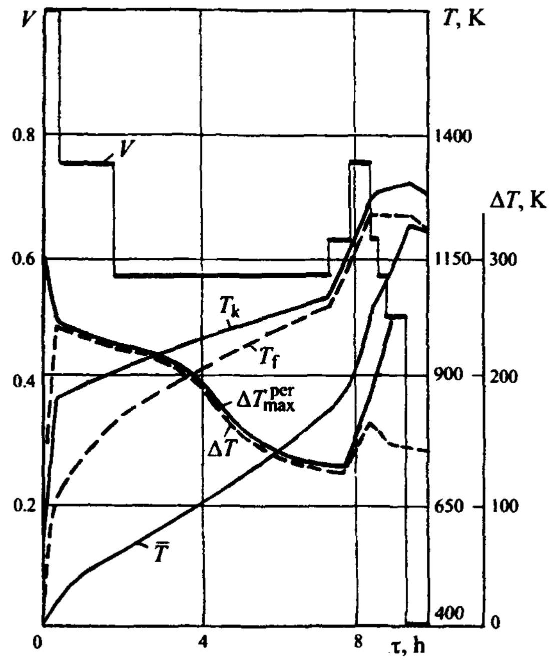

Fig. 2. Optimum control of the firing conditions for solid brick in a furnace with radiating walls.

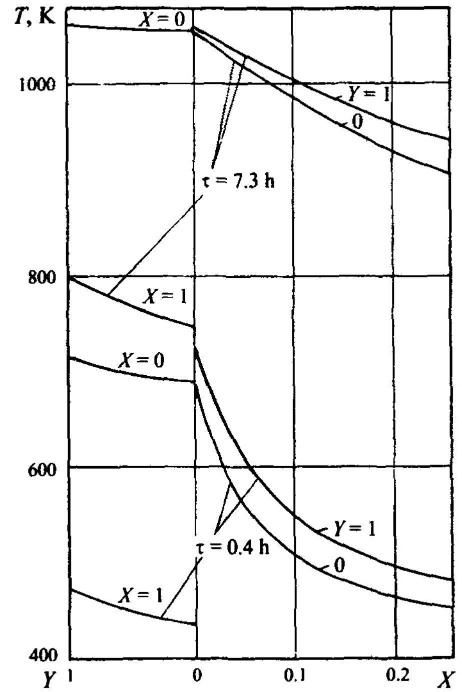

Fig. 3. Temperature variations with time along the length and across the thickness of the article.

The algorithm of the numerical solution of the problem based on the finite difference method cited in [7] takes into account the restrictions (3) – (6) in different combinations, which makes it possible to vary the strategy in order to obtain the optimum controlling effect in the heat treatment of ceramic articles in furnaces using different kinds of fuel, including electric power.

In the calculation of the given example it was taken that $P_1 = P_2 = P_3 = 1$. The following restrictions were used: $V_{min} = 0$, $V_{max} = 1.0$, $T_{s,max} = 1253$ K, $T_{k,max} = 1373$ K. The restriction for the emerging thermoelastic stresses and permissible temperature differences in an article was calculated according to the recommendation in [5]. The calculations were performed in Pascal. The computational method was as follows: the cooling zone was calculated based on the preassigned temperature of the fired articles at the beginning of the cooling zone, and the parameters of the air coming from the cooling zone to the heating zone were determined. Then the parameters of the heating and firing zones were calculated and the earlier accepted parameters of the articles at the exit from the firing zone were refined. If the discrepancy did not exceed 1%, the calculation was regarded as complete. After that the optimization problem for the firing zone was solved.

The temperature drops arising in an article are to a great extent determined by the heat flow from the radiating wall. This can be seen in Fig. 1, where a temperature drop appears at $Y = Z = 0$ between the $X = 0$ and $X = 0.9$ sections ($X = x/l$), whereas the heat flow on the wall surface is equal to q_k and the time the articles spend in the firing zone is τ.

The change in the controlling effect $V(\tau)$ for the described example is shown in Fig. 2 which additionally represents the rate of increase in the average mass temperature of the articles $\bar{T}(\tau)$ which make up the charge on the firing car, the temperature of the article surface T_f at the point whose coordinates are $X = 0$ and $Y = 0$, the temperature of the radiating wall surface T_k, the maximum permissible temperature difference in the article T^{per}_{max}, according to the data in [5], and ΔT arising in the article. As can be seen, the regulation of the thermal energy input from the radiating wall in the firing zone should be positional. At the same time, in order to create optimum firing conditions in the furnace, it is necessary to have the maximum possible power in the heaters available for the first positions of the firing cars in the firing zone, for the purpose of developing a heat pulse directed deep into the articles. The duration of this pulse ($\tau = 0.4$ h) in our example is limited by the temperature stresses arising in the articles. As the articles become heated, the controlling effect first decreases and then increases, which is due to the influence of imposed restrictions (3) – (6) on the process of article heating. The second decrease in the controlling effect at $\tau = 7.3$ h is caused by the restriction imposed on the maximum temperature of the article surface. In this case, the power consumption per each conventional solid brick in firing amounts to 1.088 kW · h.

An analysis of the development of the controlling effect reveals the need to have an area at the end of the firing zone in which the temperature field would be leveled over the entire bulk of the fired articles.

When furnaces with radiating walls are equipped with electric heaters placed on refractory brick shelves along the length of the firing zone, the power of the heaters cannot be regulated with respect to the car positions, and, consequently, the firing conditions cannot be optimized. The use of such heaters providing for $\bar{q}_k = 9.5 \text{ kW/m}^2$ and making it possible even with this minimum thermal capacity to heat the articles in the firing zone up to the temperature required for firing, within 2.5 hours after the article arrives at the firing zone, will cause an excess in the thermal stress permissible in the article, which will result in defective products.

Figure 3 shows the temperature variations in the longitudinal and lateral sections of the article. It is evident that the maximum possible temperature difference inside the article is observed along the axis of the article (axis X) at $Y = Z = 0$ in the initial stage of heating.

Thus, the developed algorithm makes it possible to determine the optimum firing conditions for ceramic products in the furnace and to control the process, at the same time ensuring high quality of the product by satisfying restrictions (3) — (6) with the maximum intensity of heat transfer to the articles and the minimum energy consumption for firing.

REFERENCES

1. S. A. Karaush, E. G. Bober', and Yu. I. Chizhik, "Calculation of temperature fields in fired ceramic articles," *Steklo Keram.*, No. 6, 13 – 15 (1996).
2. B. A. Lishanskii, B. F. Bludov, A. V. Lazurenko, et al., "Optimization of the process of firing of ceramic articles," *Izv. Vuzov, Ser. Stroitel'stvo*, No. 4, 54 – 59 (1995).
3. S. A. Karaush, "Criteria for temperature control in the firing of ceramic articles," *Steklo Keram.*, No. 5, 3 – 5 (1998).
4. S. A. Karaush, Yu. I. Chizhik, and E. G. Bober', "Optimization of the charge of ceramic articles depending on their heat absorption from radiating furnace walls," *Steklo Keram.*, No. 6, 25 – 27 (1997).
5. S. A. Blokh, *Thermal Technological Processes in Accelerated Firing of Ceramics* [in Russian], Naukova Dumka, Kiev (1979).
6. A. G. Butkovskii, S. A. Malyi, and Yu. N. Andreev, *Optimum Control of the Heating of Metals* [in Russian], Metallurgiya, Moscow (1972).
7. V. V. Salomatov, E. G. Bober', and Ya. Yu. Saifarov, *Optimization of the Heat Treatment of Metal Before Rolling as an Energy Saving Method* [in Russian], Novosibirsk (1988).